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Fabien Malbet. Probing the close environment of young stellar objects with interferometry. 2003.
hal-00000235

HAL Id: hal-00000235

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Preprint submitted on 12 Mar 2003

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Probing the close environment of young stellar objects with interferometry

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Abstract. The study of Young Stellar Objects (YSOs) is one of the most exciting topics that can be undertaken by long baseline optical interferometry. The magnitudes of these objects are at the edge of capabilities of current optical interferometers, limiting the studies to a few dozen, but are well within the capability of coming large aperture interferometers like the VLT Interferometer, the Keck Interferometer, the Large Binocular Telescope or 'OHANA. The milli-arcsecond spatial resolution reached by interferometry probes the very close environment of young stars, down to a tenth of an astronomical unit. In this paper, I review the different aspects of star formation that can be tackled by interferometry: circumstellar disks, multiplicity, jets. I present recent observations performed with operational infrared interferometers, IOTA, PTI and ISI, and I show why in the next future one will extend these studies with large aperture interferometers.

Keywords: Interferometry, Optical, Infrared, Star Formation, Young Stellar Objects, Pre-Main Sequence Stars

1. Introduction

When trying to understand the origin of our planetary system, one has basically two approaches: (i) looking for other existing planetary systems in the universe to characterize them or (ii) investigate how stellar systems have been forming. By studying young stellar objects (hereafter YSOs) in our Universe, i.e. stars in their early stages of evolution, one focuses our attention to the second approach.

So far, these objects have been extensively observed by spectrophotometry with seeing-limited resolution that corresponds at best to a hundred of astronomical units for typical star formation regions, thus many questions are still *unresolved*¹ because our incapability to disentangle the various phenomena at smaller scales. The advent of millimeter-wave interferometry, adaptive optics imaging and space telescope observations in the last decade allowed us to probe these systems closer to the star (down to 10 AU) but not close enough to probe inner solar system scales. Therefore long baseline optical interferometry with milli-arcsecond resolution corresponding to a tenth of a Earth orbit radius

¹ Pun intended as pointed out by JDM



is an essential tool to unravel the nature of the physical phenomena occurring in the early stage of star and planet formation.

In this paper, Sect. 2 briefly reviews the current knowledge about YSOs, then Sect. 3 describes the first results obtained with presently operational interferometers and finally Sect. 4 introduces some expected science objectives that will result from interferometric facilities with large apertures that are being built, such as the VLT Interferometer, the Keck Interferometer, the Large Binocular Telescope or 'OHANA.

2. Stellar formation at high spatial resolution

The star formation process of solar-type stars lasts about 10 Myr. The scenario of star formation has been categorized in classes of objects corresponding to different stages of evolution (André, 1994) from class 0 to class III. During the first 10,000 yr, the about 10 pc-wide clouds at the origin of stellar systems collapse as a result of reaching their critical mass. Since the clouds are initially rotating, they fragment in flattened rotating structures called pre-stellar class 0 cores and observed at the sub-millimeter wavelengths (Ward-Thompson et al., 1994) since due to the large opacity the energy released during the collapse cannot escape in the visible domain. After about 100,000 yr, the collapsing envelopes around class I protostars dissipate and reveal the inner part of class II systems composed of a protostar usually surrounded by an active accretion disk and a strong bipolar jet. The systems are now shining at shorter wavelengths in the infrared domain, since the main sources of radiation are the disk and the young stars still contracting. At that stage, the extent of the protoplanetary system reaches up to 1500 AU. Later on, at about 1 Myr, the gas reservoir has dissipated and the accretion stops. The class III stars, with some planetesimals and forming planets orbiting around it, are now shining mainly in the visible, a tenuous disk remains when the star arrives on the main sequence, resulting from the collisions of the planetesimals. In this paper we focus our attention on class II systems, targets of interests for optical interferometry.

The first evidence for the presence of circumstellar disks around young stars came from the advent of infrared detectors and subsequent surveys (Mendoza, 1966; Mendoza, 1968) which culminated with the IRAS survey in the early 1980's, as well as from the first UV space observations (IUE). Indeed young stars exhibit an important UV and IR excess that can even exceed the stellar luminosity. Using disk models originally developed by Shakura and Sunyaev (1973) and Lynden-Bell

and Pringle (1974), several teams (e.g. Bertout, Basri and Bouvier, 1988) showed that these excesses came respectively from the radiation of the circumstellar matter orbiting at lower effective temperature in the disk and from the interaction between the disk and the slowly rotating star. These models work well for many young systems, but for some, the spectral energy distributions (SEDs) display even larger excesses, explained by passive flaring disk models (Adams, Shu, Lada, 1988).

Millimeter-wave interferometry succeeded in resolving some of the systems with sub-arcsecond resolution (see for example UY Aur rotating disk revealed by Dutrey et al., 1998). At about the same time, adaptive optics on 4-m class telescopes and the Hubble Space Telescope (HST) directly brought to view such disks at visible and near-infrared wavelengths (see e.g. HK Tau B by Stapelfeldt et al., 1998 and HV Tau by Monin and Bouvier, 2000). In fact most of these disks are observed edge-on, because the contrast between the star and the disk is decreased by the absorption of the stellar light by the central part of the disk. The disk is seen in stellar light, scattered in the upper part of the disk atmosphere. The extent of these systems is about 100-200 AU with typical spatial resolution of 10 to 20 AU.

The Herbig-Haro 30 object observed by the HST in forbidden lines and in the continuum (Burrows et al., 1996) brought a lot of information. The relevant region of investigation lies within the 10 AU from the center where the accretion disk interacts with the star and the base of the bipolar jet is forming. One does not know precisely how these different phenomena work and interact. Is the accreting matter falling onto the star through the equatorial plane or along magnetosphere field lines? Is the jet engine the rotating star or the upper part of the disk atmosphere? Where do planets form: in the outer part of the disk or at the locations known for the solar system? What is the physical phenomenon at the origin of the viscous dissipation: pure hydrodynamical turbulence or manifestations of the magnetic field? What is the disk chemistry? What is the spatial distribution of the matter? All these questions can be investigated by visible and infrared long-baseline interferometry.

The current capabilities of optical² long baseline interferometers (with [0.5–10 μm] spectral coverage, baselines up to several hundreds of meters) gives us the characteristic range of spatial scales: between 0.1 and 10 AU, and a temperature range between few 100 K to 5000

² When using the term *optical*, I refer to both the *visible* and *infrared* wavelength domains.

K. With these numbers in mind, one can list in more detail what can be investigated by optical interferometry:

- Star surfaces: apparent diameters of young stars are typically 0.1 mas, i.e. they will be barely resolved. In addition the circumstellar matter around them might pollute diameter measurements. However weak-line T Tauri stars, which are class III stars, are believed to have lost their accretion disk and therefore some determination of stellar parameters like the radius, effective temperature or even limb-darkening might be possible.
- Multiplicity: about 80% of young stellar systems are expected to be multiple (Reipurth and Zinnecker, 1993). The binary frequency has so far been investigated in the domain of spectroscopic binaries; and visual and adaptive optics binaries, and interferometric observations will fill the gap between the two. Using interferometric data to get the orbit of known spectroscopic binaries will allow to derive their mass accurately.
- Circumstellar disks: optical interferometry allows to study the thermal emission of the disks rather than the stellar light scattered by the disk. Therefore one has access to quantities like the temperature and eventually their surface density distributions.
- Accretion: in the current paradigm, accretion occurs in a Keplerian disk. With some spectral resolution, one will verify this motion and even measure departure from the Kepler law (see Sect. 4.2.3). The terminal accretion is not yet understood and neither is the link with the star magnetosphere. With spectral and spatial resolution, one can solve the kinematics of the inner region.
- Ejection: one does not know yet if the origin of the jet comes from the stellar dipole/quadrupole or from the disk. Interferometry will allow to probe the base of the jets and determine their opening angle, which is a critical parameter (see Sect. 4.2.2). One can also investigate the link between the jets at small scales and larger outflows.
- Formation of planets: currently giant planets are believed to be born in the outer region of active accretion disk and to then migrate inward closer to the star. Such phenomenon perturbs the disk and may leave detectable signatures like the presence of gaps or gravitational waves in the disk.
- Star formation scenarios: YSOs correspond to a collection of different objects at different times of evolution ranging from classical T Tauri stars to weak-line T Tauri stars, and also include FU

Orionis objects which are believed to be T Tauri stars for which the disk undergoes an accretion outburst, and, intermediate mass counterparts called Herbig Ae/Be stars. Observing these different classes of objects will give us clues on the evolution of young stars.

Most of these phenomena takes place in a sub-AU region where the dynamic time scale is less than a year for solar mass stars and even shorter for more massive stars. Therefore one should also consider that the investigated physics will no longer be stationary but for a large part dynamical.

Finally, I would emphasize that observing YSOs will bring us a wealth of information also useful for other types of astrophysical objects such as active galactic nuclei, cataclysmic variables, radio-jets,... since it will shed lights on universal physical processes like the nature of viscosity, the role of magnetic field, how dust grains form and grow, and the link between accretion and ejection processes.

3. First results from operational small aperture optical interferometers

In this section, I summarize the results obtained so far in optical interferometry on the brightest objects and I show that interferometry has already modified our understanding of disks.

These results come from three infrared interferometers: the *Palomar Testbed Interferometer (PTI)* located on Palomar Mountain (California, USA) and operating two pairs of siderostats in the *H* and *K* bands; the *Infrared and Optical Telescope Array (IOTA)* located on Mount Hopkins (Arizona, USA) operating in the *H* and *K* bands with two relocatable siderostats; and the *Infrared Spatial Interferometer (ISI)* located on Mount Wilson (California, USA) and operating at 10 μm with a heterodyne detection.

The list of refereed papers that describe all YSO observations carried out to date is: FU Ori at PTI (Malbet et al., 1998); AB Aur at IOTA and PTI (Millan-Gabet et al., 1999); T Tau, MWC 147, SU Aur and AB Aur at PTI (Akeson et al., 2000); about 15 Herbig Ae/Be stars at IOTA (Millan-Gabet, Schloerb and Traub, 2001); and the massive star LkH α 101 at ISI (Tuthill et al., 2002).

Most of the objects observed so far are either intermediate mass objects or low-mass stars with an active accretion disk, because their magnitudes are close to the sensitivity limit of the instruments. The measurements are limited to visibility amplitudes and therefore are mainly focused on the disk physics.

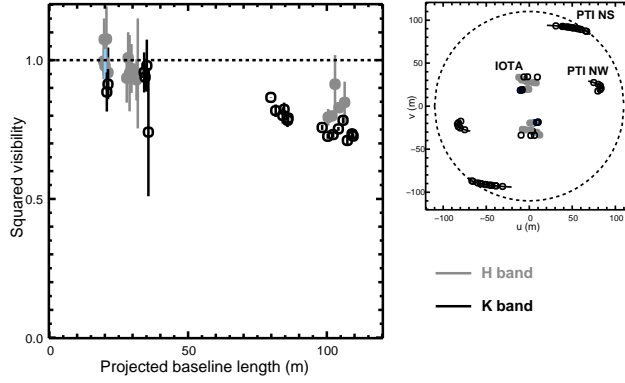


Figure 1. Interferometric observations (Malbet et al., 1998; Malbet and Berger, 2001) of FU Ori collected at IOTA and PTI between 1997 and 2000. Gray circles correspond to H band, and black circles to K band. Left panel: squared visibilities as a function of the projected baseline. Right panel: (u, v) coverage.

3.1. CONSTRAINT ON T TAURI DISKS

One interesting example is the case of FU Ori. This system is known to be composed of a T Tauri star with a disk undergoing an accretion outburst (Hartmann and Kenyon, 1996). Therefore this system is brighter by more than 2-4 magnitudes than other classical T Tauri systems and the disk emission dominates the spectral energy distribution. This object is therefore an ideal target to study disk accretion, since at near-infrared wavelengths the observations are not contaminated by other physical processes.

Figure 1 shows a typical example of data collected with IR interferometers. The visibility reduction of 15-30% at long baselines corresponds to the resolution of a structure of size of the order of 1 mas, corresponding to 0.5 AU at the distance of the Orion cloud. Moreover, the visibility drop in H is smaller than in K , meaning that the size of this structure decreases with the wavelength faster than the resolution λ/B .

The data is consistent with the standard disk model used to fit the SED. In fact the data points are lying exactly where they were expected to be from disk model predictions (Malbet and Bertout, 1995).

However the data collected in the following years in the H and K bands show square visibilities which differ more than expected by the standard accretion disk model. A way to investigate this departure from the standard model is to derive a direct measure of the temperature law. Adams, Shu, Lada (1988) have introduced an *ad-hoc* prescription

to describe the variation of the effective temperature through the disk:

$$T = T_0 \left(\frac{r}{r_0} \right)^{-q} \quad \text{with} \quad 0.5 \leq q \leq 0.75 \quad (1)$$

A value of $q = 3/4$ corresponds to the standard geometrically thin disks and $q = 0.5$ describes some type of flaring passive disks. Beckwith et al. (1990) surveyed a large number of sources at millimeter wavelength and could derive values of q which indeed range between 0.5 and 0.75.

In the case of FU Ori, Malbet (2002) obtained $q \simeq 0.6 \pm 0.2$, compatible with the SED derived value of $q \simeq 0.75$. However, in the future more precise observations might no longer be interpreted with this simple disk model. The reason for such behavior can be explained by the fact that interferometry probes the inner region of the disk whereas the SED is more sensitive to the outer regions. One speculates that the change of temperature law is due to a change of the accretion rate in the inner part of the disk due to the presence of a jet that removes material from the disk.

The case of FU Ori is simple since the dominant physical process is the accretion. In low-mass stars YSOs, some other effects can play a substantial role, like the heating of the disk photosphere by the central star (Calvet et al., 1991; Malbet and Bertout, 1991; Chiang and Goldreich, 1997). This creates an upper layer which can have higher temperature than the layer located at lower altitudes, impacting both the SED and the visibilities.

To describe this stellar reprocessing in the disk, there exists no simple models. Chiang and Goldreich (1997) presented a two-layer model that is successful in interpreting SEDs. More recently Lachaume, Malbet and Monin (2003) generalized the Chiang and Goldreich model to include the effect of viscous dissipation. They have applied their model to interferometric observations made by Akeson et al. (2000) at PTI and succeeded in fitting reasonably well both SED and visibilities. It therefore shows that interferometric data can provide valuable information on the physics of the disk.

3.2. DISKS AROUND HERBIG Ae/Be STARS ARE NOT AS EXPECTED

Herbig Ae/Be stars (HAEBEs) are young stars of intermediate mass (a few solar masses). They exhibit an infrared excess like the lower mass T Tauri stars, but there has been a controversy on the origin of this excess (Hillenbrand et al., 1992; Boehm and Catala, 1994). Since they are brighter than T Tauri stars, they have been excellent candidates to be observed by infrared interferometers.

Millan-Gabet et al. (1999) observed the first Herbig Ae star AB Aurigae in 1997-1998 and discovered that the standard disk model was

not compatible with the data. In brief, the object was over-resolved compared to the prediction of the model. This result was confirmed by observations of about 15 targets of the same type by Millan-Gabet, Schloerb and Traub (2001).

The best interpretation of the data is to consider that the star is surrounded by a ring of material located at sub-AU distances, namely 0.3 AU for AB Aur. Tuthill, Monnier and Danchi (2001) obtained similar results on the more massive star LkH α 101, and proposed that this ring is the result of the sublimation of the dust orbiting the star, such that the ring radius gives an estimate of the distance where dust sublimation occurs.

Monnier and Millan-Gabet (2002) compiled measurements made with the various interferometers and put them in a diagram with the ring inner radius as a function of the central star luminosity. The correlation seems to follow the law that can be expected by a simple model of dust sublimation in r^{-2} . In parallel, Natta et al. (2001) who worked on the SEDs measured by ISO were not able to reproduce the gap occurring in the near-infrared with the standard model. By truncating the inner part of the disk and heating the inner part of the disk by the central star, they were able to fit both the ISO data and the interferometric observations. The ring proposed by Millan-Gabet and collaborators would then be the inner part of a disk which is puffed up by the stellar radiation and may also shadow part of the disk (see also the model proposed by Dullemond, Dominik and Natta, 2001).

It is less clear whether T Tauri stars follow the same behavior. As a matter of fact, the regions for dust sublimation models and accretion disk are very close for these objects. More detailed studies are therefore required for these low-mass objects and should be possible with large aperture interferometers.

3.3. CONCLUSIONS AND PERSPECTIVES

One starts constraining the physical conditions in disks with different techniques (millimeter-wave interferometers, adaptive optics, HST, optical interferometry), but optical interferometry is the only current technique which constrains the inner 10 AU of the disk. The first results on low-mass T Tauri stars are consistent with standard accretion disk models, but more complex environments appear to be required for the more massive HAEBE stars with passive disks.

One needs to improve the wavelength coverage since it is a good way to constrain temperature laws. Ideally J , H , K , L and N data sets and better (u, v) coverage are desirable.

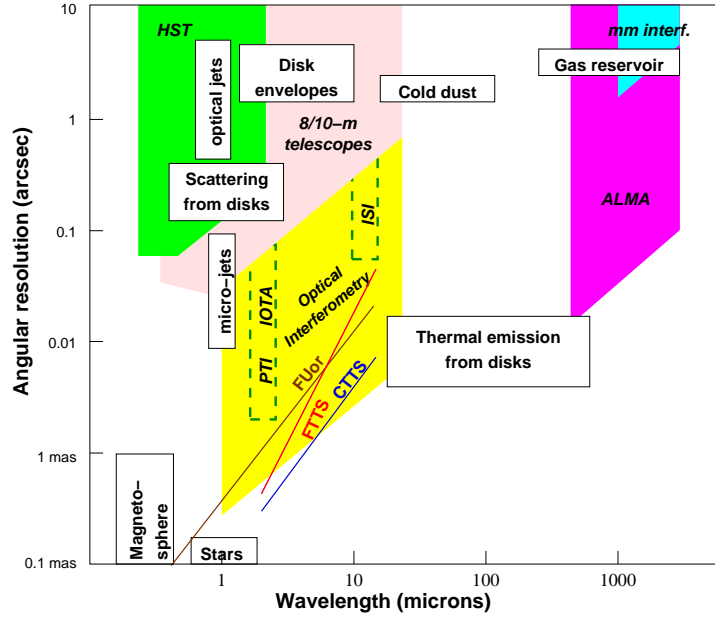


Figure 2. Resolution diagram showing angular resolution as a function of wavelength. Competitive instruments from optical to millimeter wavelengths are displayed together with the main issues in the star formation field. Also present are the operational infrared interferometers that have already produced some astrophysical results: IOTA, PTI and ISI.

The coming facilities with large apertures like the VLTI, KI, LBT and ‘OHANA will certainly boost these studies by bringing higher sensitivity, better (u, v) coverage, access to phases and eventually to images. Finally, it is also essential to continue the theoretical modelling effort, particularly relevant physics of the inner disks.

4. Expected science from coming large aperture interferometers

Some very interesting science has been carried out with current interferometers with small apertures. In this section, I present in the YSO field the impact of anticipated improvements that will be accessible with interferometers with large apertures like the VLTI, the Keck interferometer, the LBT and ‘OHANA.

4.1. IMPROVEMENTS EXPECTED FROM LARGE INTERFEROMETERS

The angular resolution and the spectral coverage offered by presently operating interferometers match almost perfectly the needs in the star

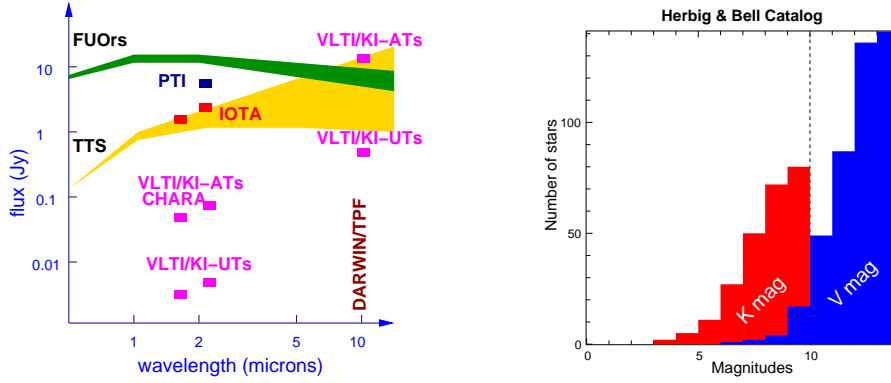


Figure 3. Left panel: Sensitivity diagram showing the flux sensitivity as a function of the wavelength in the optical range. Sensitivities from IOTA and PTI are represented as well as the typical flux for T Tauri stars (TTS, both classical ones and those with a flat IR spectrum) and FU Orionis stars (FUOrs). Right panel: K and V histograms of objects listed in the Herbig & Bell catalog (Herbig and Bell, 1988). A limiting magnitude of $K = 10$ (dashed line) is a conservative value for an interferometer with large apertures.

formation domain (see Fig. 2). YSOs are usually at the limit of detection of present small aperture telescopes with a typical K limiting magnitude of 6. Only very few objects can be observed and are mainly the more massive ones like Herbig Ae/Be stars (see results presented in Sect. 3).

Usually in interferometry, the magnitudes of the objects are not the unique detection criterion but the expected visibility is also important: interference fringes must be detected and the amplitude of these fringes are proportional to the correlated magnitude, i.e. both to the flux and to the visibility amplitude at the given spatial frequency. However in young stars, since most structures are barely resolved, one does not expect the correlated magnitude to be smaller by 1 or 2 magnitudes than the object magnitude and the object magnitude remains a good criterion. The left panel of Fig. 3 displays the spectral energy distribution for different types of low-mass stars located respectively at 150 pc and 450 pc: classical T Tauri stars, T Tauri stars with a flat infrared excess and FU Orionis objects. HAEBE stars and more massive stars usually lie far above these curves. On the same figure, I indicate the sensitivity limits of PTI and IOTA demonstrating that these interferometers are at the very edge of the domain. Expected performances from interferometers using 2m (ATs) and 8-10m (UTs) class telescopes like the VLTI, KI, LBT or 'OHANA show that those interferometers are sensitive enough to fully investigate these objects at least in the near-infrared. In fact the right panel of Fig. 3, which plots the K and

V histograms of the young stars listed in the Herbig & Bell catalog (Herbig and Bell, 1988) shows that with a K limiting magnitude of 10, a conservative value, several hundreds of objects are observable. With such a high number of potential targets, one can now consider carrying out surveys in order to perform statistical studies where one would look for correlations between visibilities and flux excesses, binary frequency, or veiling.

Another limitation of presently operating telescopes is the number of operational baselines. IOTA is limited to a maximum baseline length of 38m, PTI can only use long baselines of 80m and 100m (see for example the (u, v) coverage of FU Orionis shown in Fig. 1). This is not sufficient to obtain a complete characterization of the resolved material. In the near future, the VLTI will be able to provide a wide coverage of a 200-m large synthetic aperture thanks to 4 relocatable auxiliary telescopes. CHARA with a maximum baseline of 350m even if with only 1-m apertures will provide more angular resolution. 'OHANA with a limited number of fixed telescopes remains interesting because of its very long maximum baseline of 800m. A high number of measurements at different spatial frequencies are also expected to lead to aperture synthesis imaging. In fact even a small number of spatial frequencies should permit to achieve parametric images using regularization methods that takes into account the astrophysical nature of the sources.

I would like to emphasize also that interferometers up to now provided only broad-band visibility amplitudes. IOTA has been upgraded to 3 telescopes and will soon provide closure phases on YSOs, an observable which gives information on the symmetry of the obscured structure. A centro-symmetric object has a zero closure phase, whereas a non centro-symmetric object has a non-zero closure phase. Lachaume, Malbet et al. (2003, 2000) simulated circumstellar disks irradiated by young stars and showed that the expected closure phase with typical 100-m baselines can reach 50 degrees. AMBER (Petrov et al., 2002) on the VLTI will also provide closure phases whenever used with a triplet of auxiliary or unit telescopes. AMBER and MIDI on the VLTI will provide for the first time spectral information on YSOs in the IR domain. With such spectral information, relative visibility amplitudes and phases through the spectrum and therefore through spectral lines can be measured. This feature should bring out a radical change in the observational constraints because it includes both morphological and kinematics information.

4.2. SOME EXAMPLES OF NEW YSO INVESTIGATIONS

In this part, I present some non-exhaustive examples of new types of observations than can be carried out with instruments providing the type of improvements listed in the previous paragraph.

4.2.1. *Planet-disk interaction*

Wolf, Henning and d'Angelo (2001) have investigated the possibility to detect the signature of a protoplanet inside a protoplanetary disk. Some exoplanets discovered by radial velocity techniques are massive giant planets located close to the parent star. This location was not predicted by theory, but since then, several models were able to explain the presence of such planets thanks to migration mechanisms in a protoplanetary disk (Nelson et al., 1998). The idea of Wolf, Henning and d'Angelo, was to see if it would be possible to detect such a gap in accretion disks that would be the signature of the presence of a giant planet. They made the prediction for mid-IR observations (MIDI on the VLTI) and demonstrated that the difference between a perfectly smooth disk and a disk with a gap leads to a change in visibility amplitudes of the order of 5%. This number is at the limit of detection for the instrument MIDI, but within realistic expectations for current near-infrared instruments or future instruments.

4.2.2. *Opening angle of microjets*

Eisloffel and Dougados (1997) and Garcia, Foy and Thiébaut (2001) proposed to investigate the morphology of jets close to the stars. Jets are an important feature of young stellar objects, almost always present whenever there is a disk. For the moment very little is known on the interaction between the disk, the stars and the jets. In fact several magneto-hydrodynamical models have been developed and optical interferometry could be the tool to test them on very high angular resolution observations.

However, even before directly testing the physics of jets, the simple observation of the opening angle of jets would bring significant constrain on models. Up to now the resolution of a single dish telescope was not sufficient to see the base of the jets. Garcia, Foy and Thiébaut (2001) used a toy model to simulate a hollow jet and computed the expected visibility of a star-jet system. The expected visibility amplitude is of the order of 50%. Garcia et al. demonstrated that RU Lupus can be observed with sufficient signal-to-noise ratio with AMBER and medium spectral resolution.

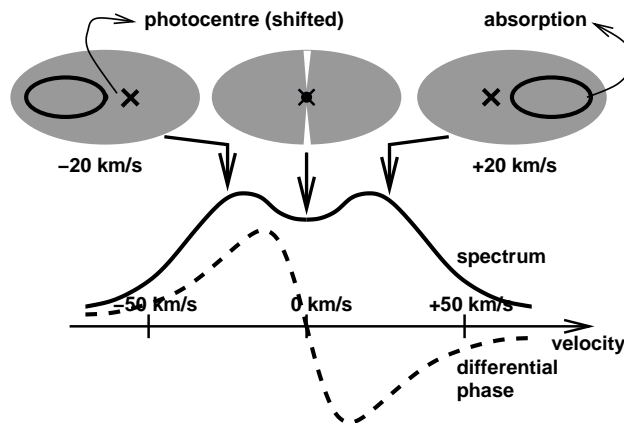


Figure 4. Principle to measure the Keplerian motion of matter inside a circumstellar disk (Lachaume et al., priv. comm.). See the text for details.

4.2.3. Probing the velocity field of disks at sub-AU scale

Spectral information is indeed the feature that could bring one the most interesting information in YSOs. Lachaume, Malbet and Monin (priv. comm.) proposed to observe circumstellar disks with enough spectral resolution to be able to detect the Keplerian motion of the matter in the disk. Kenyon, Hartmann and Hewett (1988) have correlated several absorption lines of the spectrum of FU Orionis in order to detect the Doppler shift signal coming from the matter orbiting around the star. They found a double peak line that could be interpreted as the evidence of Keplerian motion in the disk. However they were not able to completely rule out the presence of a spectroscopic binary in the system. With AMBER and the spectral information, one can follow the position of the photocenter by measuring the wavelength-dependent phase. Figure 4 shows the principle of the measure: in the blue part of the absorption line the matter which absorb the light is located on one part of the disk and therefore the photocenter of remaining light is shifted to the opposite side of the disk. For the red part of the spectrum, the signal is shifted in the opposite direction. In the middle of the line the disk is symmetrical and the photocenter is aligned with the star. Therefore the phase will increase positively in the blue part of the line goes through zero at the systemic velocity and increase negatively in the red part. The shape of this curve can be compared to the one expected from a pure Keplerian motion. Any departure would be an interesting test of the physics of the disk. The signal will be faint, but the plan is to correlate the signals from various spectral lines as is done for radial velocity measurements.

5. Conclusion

I reviewed the science that has been performed so far with existing interferometers. Some important information has been obtained mainly for the most massive objects already observable. A wider range of issues can be addressed by large interferometers since a large fraction of YSOs will be observable with a large number of different instrumental configurations. This astrophysical domain is therefore undoubtedly progressing thanks to this new high angular resolution technique and the results will be of importance not only for star formation but also for general physical processes like the origin of turbulence, the interaction between accretion and ejection.

However, the wavelength coverage of current and planned instruments does not cover yet the visible part of the spectrum, the field is limited to compact objects and imaging is still a goal. For all these reasons, star formation remains a major scientific drivers for next generation interferometric instruments.

Acknowledgements

I would like to thank J.-P. Berger, R. Lachaume and R. Millan-Gabet for very interesting discussions and inputs for this review that was initially prepared for the SPIE'2002 meeting. I am also grateful to R. Millan-Gabet and J.D. Monnier who reread the manuscript.

References

- Adams, F. C., Shu, F. H., Lada, C. J., The disks of T Tauri stars with flat infrared spectra. *Astrophysical Journal*, 326:865–883, 1988.
- Akeson, R. L., Ciardi, D. R., van Belle, G. T., Creech-Eakman, M. J., Lada, E. A., Infrared Interferometric Observations of Young Stellar Objects. *Astrophysical Journal*, 543:313–317, 2000.
- Akeson, R. L., Ciardi, D. R., van Belle, G. T., Creech-Eakman, M. J., Constraints on Circumstellar Disk Parameters from Multiwavelength Observations: T Tauri and SU Aurigae. *Astrophysical Journal*, 566:1124–1131, 2002.
- André, P. Observations of protostars and protostellar stages. In T. Montmerle, C.J. Lada, I.F. Mirabel and J. Tran Thanh Van, editors, *The cold Universe; Proceedings of the XXVIIIth Rencontres de Moriond*, pp. 179, 1994. Eds Frontières, Paris.
- Beckwith, S. V. W., Sargent, A. I., Chini, R. S., Guesten, R., A survey for circumstellar disks around young stellar objects. *Astronomical Journal*, 99:924–945, 1990.

- Berger, J.P., Interférométrie et formation stellaire. Perspectives pour une instrumentation en optique intégrée. *Ph.D. Thesis*, University of Grenoble, 1998.
- Bertout, C., Basri, G., Bouvier, J., Accretion disks around T Tauri stars. *Astrophysical Journal*, 330:350–373, 1988.
- Boehm, T., Catala, C., Forbidden lines in Herbig Ae/Be stars: the [OI](1F) 6300.31Å and 6363.79Å lines. I. Observations and qualitative analysis. *Astronomy and Astrophysics*, 290:167–175, 1994.
- Burrows, C. J., et al., Hubble Space Telescope Observations of the Disk and Jet of HH 30. *Astrophysical Journal*, 473:437, 1996.
- Calvet, N., Patino, A., Magris, G. C., D'Alessio, P., Irradiation of accretion disks around young objects. I - Near-infrared CO bands. *Astrophysical Journal*, 380:617–630, 1991.
- Chiang, E. I., Goldreich, P., Spectral Energy Distributions of T Tauri Stars with Passive Circumstellar Disks. *Astrophysical Journal*, 490:368, 1997.
- Dullemond, C. P., Dominik, C., Natta, A., Passive Irradiated Circumstellar Disks with an Inner Hole. *Astrophysical Journal*, 560:957–969, 2001.
- Dutrey, A., Guilloteau, S., Prato, L., Simon, M., Duvert, G., Schuster, K., Menard, F., CO study of the GM Aurigae Keplerian disk. *Astronomy and Astrophysics*, 338:L63–L66, 1998.
- Eisloffel, J., Dougados, C., Outflows from Young Stars. *Science with the VLT Interferometer*, 240, 1997.
- Garcia, P. J. V., Foy, R., Thiébaud, E., Into the twilight zone: reaching the jet engine with AMBER/VLTI. ESO conference, J.F. Alves and M.J. McCaughrean eds, 267, 2001.
- Hartmann, L., Kenyon, S. J., The FU Orionis Phenomenon. *Annual Review of Astronomy and Astrophysics*, 34:207–240, 1996.
- Herbig, G. H., Bell, K. R., Catalog of emission line stars of the Orion population : 3 : 1988. *Lick Observatory Bulletin*, Santa Cruz: Lick Observatory, 1988.
- Hillenbrand, L. A., Strom, S. E., Vrba, F. J., Keene, J., Herbig Ae/Be stars - Intermediate-mass stars surrounded by massive circumstellar accretion disks. *Astrophysical Journal*, 397:613–643, 1992.
- Kenyon, S. J., Hartmann, L., Hewett, R., Accretion disk models for FU Orionis and V1057 Cygni - Detailed comparisons between observations and theory. *Astrophysical Journal*, 325:231–251, 1988.
- Lachaume, R., Structure des disques d'accrétion autour des étoiles jeunes de faible masse. *Ph.D. Thesis*, University of Grenoble, 2003.
- Lachaume, R., Malbet, F., Monin, J.-L., The vertical structure of T Tauri accretion disks. III. Consistent interpretation of spectra and visibilities with a two-layer model. *Astronomy and Astrophysics*, in press, 2003.
- Lynden-Bell, D., Pringle, J. E., The evolution of viscous discs and the origin of the nebular variables.. *Monthly Notices of the Royal Astronomical Society*, 168:603–637, 1974.
- Malbet, F., et al., FU Orionis Resolved by Infrared Long-Baseline Interferometry at a 2 AU Scale. *Astrophysical Journal*, 507:L149–L152, 1998.
- Malbet, F., Lachaume, R., Monin, J.-L., Berger, J.-P., Probing the inner part of protoplanetary disks with the VLTI. *SPIE*, 4006:243–251, 2000.
- Malbet, F., Berger, J.-P., The nature of the circumstellar matter around FU Orionis. *SF2A-2001: Semaine de l'Astrophysique Française*, p. 457, 2001.
- Malbet, F., Young stellar objects science with interferometry: a review. *SPIE*, 4838: in press, 2002.

- Malbet, F., Bertout, C., The vertical structure of T Tauri accretion disks. I - Heating by the central star. *Astrophysical Journal*, 383:814–819, 1991.
- Malbet, F., Bertout, C., Detecting T Tauri disks with optical long-baseline interferometry.. *Astronomy and Astrophysics Supplement Series*, 113:369, 1995.
- Millan-Gabet, R., Schloerb, F. P., Traub, W. A., Malbet, F., Berger, J. P., Bregman, J. D., Sub-Astronomical Unit Structure of the Near-Infrared Emission from AB Aurigae. *Astrophysical Journal*, 513:L131–L134, 1999.
- Millan-Gabet, R., Schloerb, F. P., Traub, W. A., Spatially Resolved Circumstellar Structure of Herbig AE/BE Stars in the Near-Infrared. *Astrophysical Journal*, 546:358–381, 2001.
- Mendoza V., E. E., Infrared Photometry of T Tauri Stars and Related Objects. *Astrophysical Journal*, 143:1010, 1966.
- Mendoza V., E. E., Infrared Excesses in T Tauri Stars and Related Objects. *Astrophysical Journal*, 151:977, 1968.
- Monin, J.-L., Bouvier, J., Disks in multiple systems: direct imaging of a nearly edge-on circumstellar disk in the young triple system HV Tau. *Astronomy and Astrophysics*, 356:L75–L78, 2000.
- Monnier, J. D., Millan-Gabet, R., On the interferometric sizes of Young Stellar Objects. *Astrophysical Journal*, 579:694–698, 2002.
- Natta, A., Prusti, T., Neri, R., Wooden, D., Grinin, V. P., Mannings, V., A reconsideration of disk properties in Herbig Ae stars. *Astronomy and Astrophysics*, 371:186–197, 2001.
- Nelson, R.P., Papaloizou, J.C.B., Masset, F., Kley, W., The migration and growth of protoplanets in protostellar discs *Monthly Notices of the Royal Astronomical Society*, 318:18–36, 2000.
- Petrov, R., et al., Using AMBER, the near-infrared VLTI focal instrument. *SPIE*, 4838: in press, 2002.
- Reipurth, B., Zinnecker, H., Visual binaries among pre-main sequence stars. *Astronomy and Astrophysics*, 278:81–108, 1993.
- Shakura, N. I., Sunyaev, R. A., Black holes in binary systems. Observational appearance.. *Astronomy and Astrophysics*, 24:337–355, 1973.
- Stapelfeldt, K. R., Krist, J. E., Menard, F., Bouvier, J., Padgett, D. L., Burrows, C. J., An Edge-On Circumstellar Disk in the Young Binary System HK Tauri. *Astrophysical Journal*, 502:L65, 1998.
- Tuthill, P.G., Monnier, J. D., Danchi, W. C., A dusty torus around the luminous young star LkH α 101. *Nature*, 409:1012–1014, 2001.
- Tuthill, P.G., Monnier, J.D., Danchi, W.C., Hale, D.D.S., Townes, C.H. Imaging the Disk around the Luminous Young Star LkH α 101 with Infrared Interferometry *Astrophysical Journal*, 577:826–838, 2002.
- Ward-Thompson, D., Scott, P. F., Hills, R. E., and André, P., A Submillimetre Continuum Survey of Pre Protostellar Cores. *Monthly notices of the Royal Astronomical Society*, 268:276, 1994.
- Wolf, S., Henning, T., d’Angelo, G., Detecting gaps in protoplanetary disks with MIDI at the VLTI. ESO conference, J.F. Alves and M.J. McCaughrean eds, 325, 2001.

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